Minority carrier lifetime and photoluminescence studies of antimony-based superlattices

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ABSTRACT

In this work, we have used the optical modulation response technique to investigate the minority carrier lifetimes in (42 Å, 21 Å) InAs/GaSb superlattices. The feasibility of using a visible 643 nm excitation source with short penetration depth was investigated by comparing the results to reference measurements performed with a 1550 nm IR laser. Minority carrier lifetimes in the range of 33 – 38 ns were achieved, in good agreement with the reference measurements. Reliable results of the minority carrier lifetimes can consequently be achieved also with short wavelength lasers, probably due to high carrier mobility, which enables a uniform distribution of excess carriers in the material. Furthermore, when comparing superlattices with essentially the same PL peak wavelength, correlation between the minority carrier lifetime and the PL intensity was observed. This shows that the PL intensity serves as a good indicator of the material quality.

Keywords: PL, heterostructure, infrared, photodetector, superlattice, minority carrier lifetime

1. INTRODUCTION

Antimony based type-II superlattices (SL) are considered to be one of the main candidates for next generation high performance infrared (IR) detectors. These SLs typically contain alternating thin layers of InAs and GaSb and the detection is based on type-II interband transitions between the hole energy levels located in the GaSb layers and electron energy levels in the InAs layers. The flexibility of the closely lattice-matched material system of InAs, GaSb and AlSb allows for engineering of the band gap for tailoring of the detection wavelength within the medium-wavelength IR (MWIR, 3-5 μm) region and the long-wavelength IR (LWIR, 8-14 μm) region. This material system has also enabled new barrier based detector structures [1-4] which are designed to reduce the problems of small bandgap material detectors, such as tunneling across the band gap and dark current related to Shockley-Read-Hall (SRH) processes.

The lifetime of minority carriers is a key parameter that defines both the dark current and quantum efficiency of photodetectors. Achievement of a long lifetime material is an important task for superlattice detector development that will advance the current state-of-the-art technology and will enable high performing detectors and FPAs. Two different optical methods that are used to extract the minority carrier lifetime from InAs/GaSb superlattice material are time-resolved PL (TRPL) [5] and optical modulation response (OMR) [6,7]. Typical lifetimes extracted for long-and mid-wavelength infrared superlattices are 30 ns and 100 ns, respectively.

In this paper, we have used the OMR technique to study the minority carrier lifetimes in three InAs/GaSb photoluminescence (PL) structures with different number of periods in the absorber: 300, 400 and 600 periods respectively. The feasibility of using a visible 643 nm laser source with short penetration depth for lifetime measurements was studied by comparing the achieved results to measurements performed on the same samples with a 1550 nm IR laser source, which penetrates much deeper into the sample. Despite the differences in excitation wavelengths and penetration depths, the results from both measurements were very similar. This indicates that the diffusion length is long enough to facilitate a homogeneous distribution of excess carriers in the material.

2. EXPERIMENTAL DETAILS

2.1 Material growth

SL confinement structures were grown in a Veeco Applied-Epi Gen III molecular beam epitaxy chamber equipped with valved cracking sources for the group V Sb2 and As2 fluxes, as wells as dual In sources for independently varying the growth rates of GaInSb and InAs. Growth was performed on 50mm diameter Te-doped n-type GaSb (100) substrates. Three different long wave (42 Å, 21 Å) InAs/GaSb superlattices with 300 period, 400 periods and 600 periods, respectively, were studied. The absorbers in each sample were sandwiched between two $AlSb_{0.92}As_{0.08}$ barriers, forming confinement structures to prevent losses at the interfaces. The superlattice absorbers were nominally doped at $p = 1\times10^{16}$ cm^{-3}.

2.2 Photoluminescence measurements

Spectral PL measurements were carried out at 77 K using a Bruker IFS-V Fourier transform (FT) spectrometer. Investigated samples were mounted on the cold finger of a liquid flow cryostat with the temperature controlled by a Lakeshore temperature controller. A laser diode (emission wavelength 643 nm) with both continuous wave (CW) and sine-wave modulation was used as excitation source. For the spectral measurements, the magnitudes of the sine-wave modulation (P_1) and CW excitation powers (P_0) were both set to 50 mW, resulting in a peak to peak intensity of 100 mW. The step-scan mode of the FT spectrometer was utilized, combined with lock-in technique to improve the signal to noise ratio and to achieve a reliable way to separate the background radiation from the PL emission. The PL signal was detected by a cooled HgCdTe detector.

2.3 Lifetime measurements

The PL frequency response from the superlattices was studied by varying the frequency of the excitation source from 50 kHz to 20 MHz while the PL intensity was recorded. A 643 nm laser source with a CW excitation power P_0 and a modulated excitation power P_1 was used to excite carriers in the material. The laser excitation gave rise to the excess carrier density given in Equation (1), where τ is the carrier lifetime and ω is the angular frequency [6].

$$\Delta n = P_0\tau + \frac{P_1\tau}{\sqrt{1+\omega^2\tau^2}}\cos(\omega t - \phi) \tag{1}$$

When approximating the excess carrier density, several assumptions were made about the absorption of the excitation power and carrier distribution within the sample. The penetration depth in the sample is short (< 0.5 μm) due to the short emission wavelength of the laser, so there will be a complete absorption of the excitation power within the absorbers of the PL structures. After laser excitation, the carriers are assumed to distribute homogeneously in the absorber before recombination. This should be a good assumption since the vertical diffusion length of electrons in the p-type absorbers is in the order of 20 μm for long wave superlattices [8]. The hole diffusion length in superlattices is shorter, however, since there is a majority carrier concentration of holes due to the p-type doping this should not limit the recombination process.

In the frequency response measurements, the CW- and the modulated excitation powers were generating excess carrier densities less than or approximately equal to the doping density and the modulated excitation power, P_1, was kept much smaller than P_0. The laser was focused to an area of 2.5×10^{-4} cm^{-2}. The generated PL signal was collected by reflective optics and detected by a pre-amplified HgCdTe detector and a lock-in amplifier, both with bandwidths of 200 MHz, see figure 1. The PL intensity varied with the frequency as in equation (2) [6].

$$I_{PL}(\omega) \propto \frac{P_1\tau}{\sqrt{1+\omega^2\tau^2}} \tag{2}$$

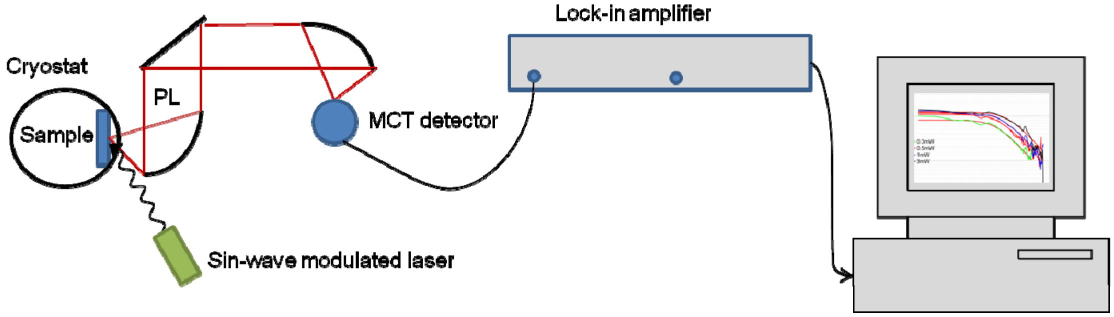

Figure 1. Experiment setup for optical modulation response measurements.

3. RESULTS

3.1 Absorption of laser light in the InAs/GaSb absorber

In measurements of the PL intensity in semiconductors and in optical measurements of the minority carrier lifetimes, several different laser types are used. Some of the commonly used ones are Argon lasers (514.5 nm), HeNe lasers (632.8 nm), Ti:Sapphire lasers (tunable between 650 nm to 1100 nm), Nd:YAG lasers (1064 nm) and laser diodes at the telecom wavelengths 1300 nm and 1550 nm. In this study a short wavelength (643 nm) laser diode was utilized and the results were compared to measurements performed with a1550 nm laser source. The transmitted intensity of the different laser sources into the material varies as: $I = I_0 e^{-\alpha x}$, where α is the absorption coefficient $\left(\alpha = \frac{4\pi k}{\lambda}\right)$, k is the extinction coefficient and λ is the wavelength. In figure 2, the calculated laser intensity decays in a (42 Å, 21 Å) InAs/GaSb superlattice for sources with different wavelengths are shown (k was estimated from the InAs and GaSb refractive indices at those wavelengths). The results show that the initial distribution of excess carriers in the absorbers will be very different in the two experiments with the 643 nm laser and the 1550 laser source. For the 643 nm laser, all of the light will be absorbed within the top 500 nm of the absorber, while the 1550 nm laser will penetrate ~3500 nm into the material.

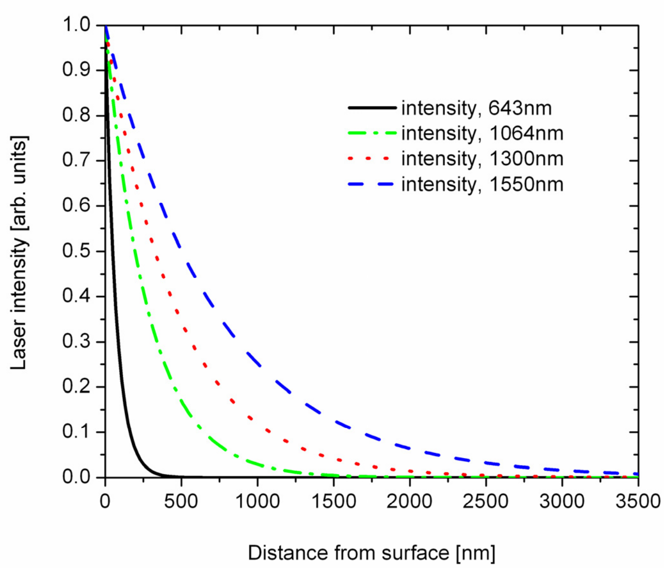

Figure 2. Calculated penetration of laser light into a (42 Å, 21 Å) InAs/GaSb absorber for four different emission wavelengths: 643 nm, 1064 nm, 1300 nm and 1550 nm, respectively.

3.2 Photoluminescence

The PL spectra of the three PL structures were measured (Figure 3) and the PL characteristics are presented in table 1. The integrated PL intensities of the 400 and 600 period samples are ~25% higher than the intensity of the 300 period sample and the FWHM are also smaller for the two thicker samples. This indicates that the material quality of the 400 and 600 period samples is slightly better than the quality of the 300 period sample. The variation of the PL peak wavelength could explain some of the difference in PL intensity but only about 5% with this small wavelength difference [9].

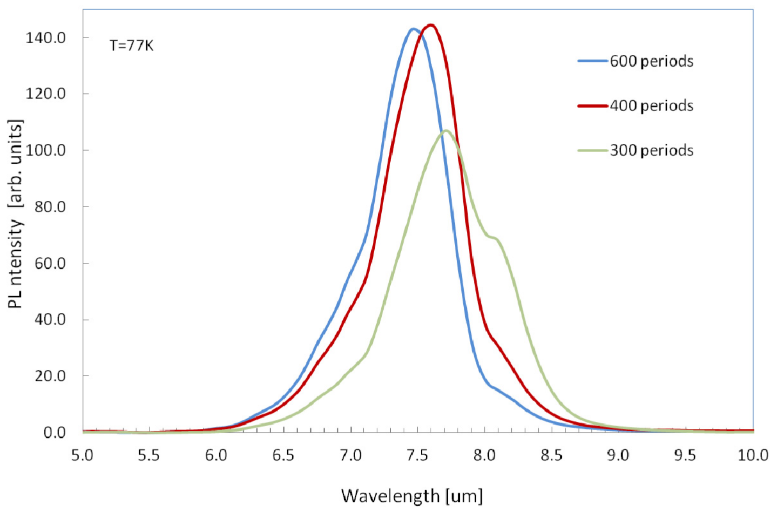

Figure 3. PL spectra of three PL structures with 300, 400 and 600 periods, respectively, of (42Å, 21Å) InAs/GaSb absorber.

Table 1. PL characteristics of three (42Å, 21Å) InAs/GaSb PL structures with 300, 400 and 600 periods, respectively.

Sample	Peak wavelength [μm]	PL peak intensity [arb. units]	Integrated PL intensity [arb. units]	FWHM [meV]
300 periods	**7.7**	**107**	**2270**	**19.2**
400 periods	**7.6**	**144**	**2820**	**14.9**
600 periods	**7.5**	**143**	**2750**	**14.5**

3.3 Minority carrier lifetime

The frequency response curves for the three different samples were measured at different CW excitation powers, while keeping the modulation excitation power constant (Figure 4). For each CW excitation power, the frequency response curve was fitted to the theoretical expression of the PL frequency response (Equation 2), with the lifetime as one of the fitting parameters. The deduced inverse lifetime was then plotted as a function of the excess carrier density (estimated using Equation (1)), see insets in figure 4.

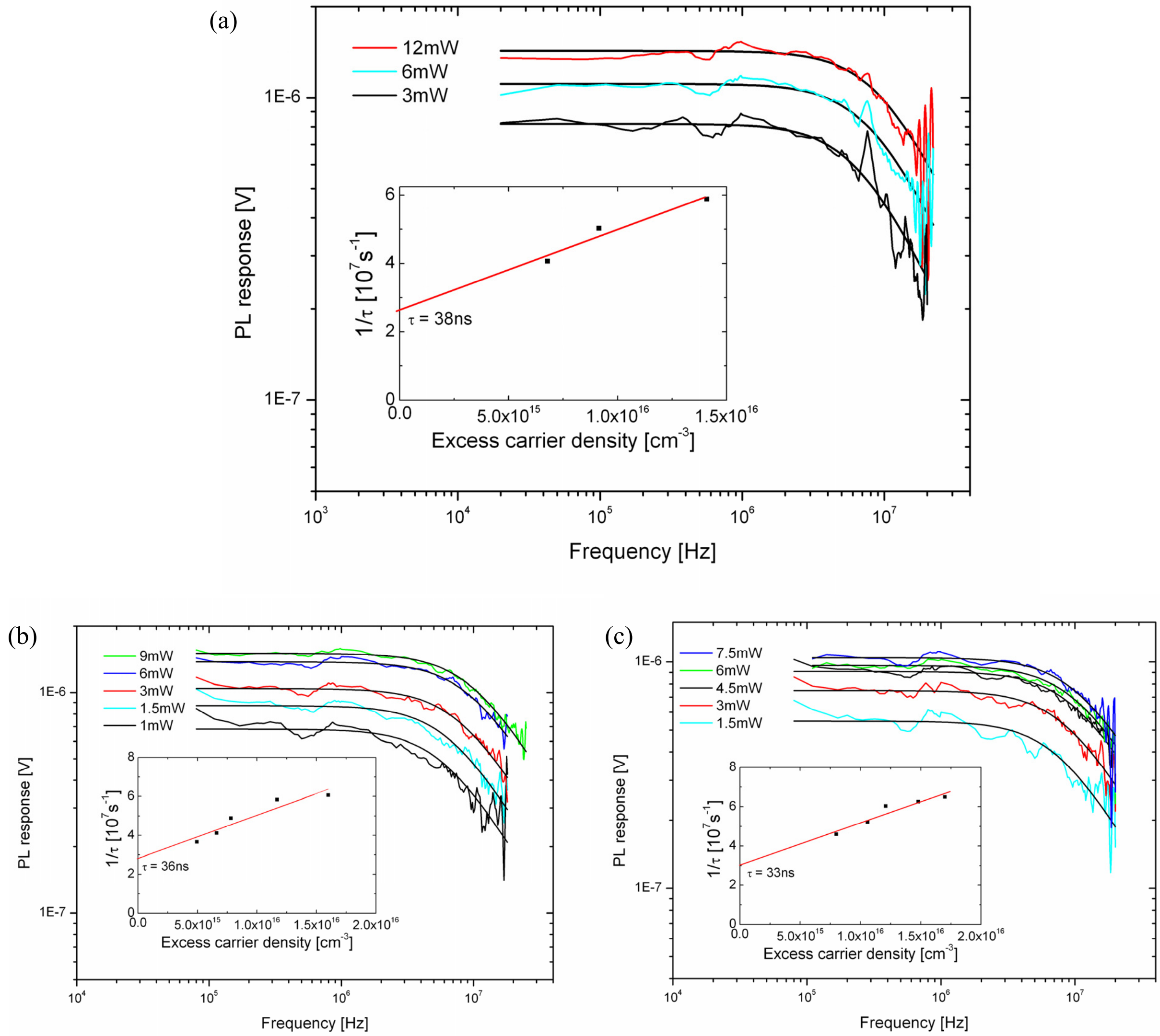

Figure 4. PL frequency response curves of (a) 600 period, (b) 400 period and (c) 300 period InAs/GaSb superlattices to a small sine wave modulation for different continuous-wave excitation powers. For each frequency response curve the lifetime is extracted by fitting of the curves to equation (2) and in the insets of each figure the inverse lifetimes are plotted versus the excess carrier density. By extrapolating the inverse lifetime to zero excess carrier density, the minority carrier lifetimes are approximated to be 38 ns, 36 ns and 33 ns for the 600 period, 400 period and 300 period superlattice, respectively.

To extract the minority carrier lifetime from the measurement results, the relation between the minority carrier lifetime and the excess carrier density was considered. The minority carrier lifetime is mainly influenced by the radiative lifetime (τ_R) the Shockley Read Hall lifetime (τ_{SRH}) and the Auger lifetime (τ_{Auger}) as given by equation (3) [10].

$$\frac{1}{\tau} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_R} + \frac{1}{\tau_{Auger}} \tag{3}$$

When excess carriers are present and the excess carrier density, Δn, is not negligible as compared to the doping density, the effective radiative lifetime of the material varies as in equation (4) and the Auger lifetime will vary as in equation (5) for a p-type sample [11].

$$\frac{1}{\tau_R} = \frac{B}{\phi}\left(p_0 + n_0 + \Delta n\right) \tag{4}$$

$$\frac{1}{\tau_{Auger}} \approx C_p\left(p_0^2 + 2p_0\Delta n + \Delta n^2\right) \tag{5}$$

In these equations B is the radiative recombination coefficient, ϕ is the photon recycling coefficient, n_0 and p_0 are equilibrium carrier densities and C_p is the Auger recombination coefficient for holes. For LW InAs/GaSb superlattices, C_p is in the order of 10^{-28} cm^6/s and B/ϕ is in the order of 10^{-10} cm^3/s [5,6]. For the moderate excess carrier densities used ($\sim 5\times10^{15} - 1.7\times10^{16}$), the Auger term in equation (3) will consequently be negligible as compared to the SRH- and radiative terms. Linear relations between the inverse lifetimes and the excess carrier densities were therefore achieved (insets, figure 4), with slopes associated with the variation of the radiative lifetime (Equation (4)). By extrapolating these linear relations to zero excess carrier density, the minority carrier lifetimes were achieved. The resulting minority carrier lifetimes of the three InAs/GaSb absorbers are presented in Table 2. The results obtained with the 643 nm laser are very similar to the results from the reference measurements performed with a 1550 nm laser. The initial difference in excess carrier distribution caused by the two different lasers (figure 2) does consequently not cause a problem for the determination of the minority carrier lifetime. This could be explained by the high mobility and thereby the long diffusion length in these LW superlattices [8]. The small discrepancy between the measurements can probably be assigned to the uncertainty in the fitting procedure of the frequency response curves, since the noise level was fairly high.

The lifetimes achieved with the 1550 nm laser also show good correlation with the PL intensity differences between the samples (Table 1). This shows that the PL intensity serves as a good indicator of the minority carrier lifetime and thereby the material quality of the sample.

Table 2. Comparison of minority carrier lifetimes of the three InAs/GaSb superlattices as measured with a 643 nm laser and a 1550nm laser, respectively.

Sample	Lifetime, 643 nm laser [ns]	Lifetime, 1550 nm laser* [ns]
300 periods	**33**	**31**
400 periods	**36**	**38**
600 periods	**38**	**38**

*Measurements performed by D. Donetsky at Stony Brook University

4. SUMMARY

A feasibility study was performed, comparing the use of a short wavelength laser for minority carrier lifetime measurements on (42 Å, 21 Å) InAs/GaSb superlattices with reference measurements performed with a 1550 nm laser source. The minority carrier lifetimes extracted using the 643 nm laser as excitation source was very similar to the reference measurements, which shows that reliable results can be achieved also with short wavelength lasers, despite the short penetration depth. Furthermore, a good correlation between the PL intensity and the minority carrier lifetime was observed, which shows that the PL intensity serves as a good indicator of the material quality in the sample.

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